

PHYSICAL PARAMETERS OF STARS
WITH HOT AND
EXTENDED ATMOSPHERES

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The present paper constitutes a report on and summary of work on stars with hot and extended atmospheres. The summary concerns the following articles:

- I. Continuum Energy Distribution of O5—G0 Stars in Terms of Spectral Gradients (Ardeberg, A. 1969, *Astron. Astrophys.* 3, 257).
- II. On the Spectral Gradient around Wave-Number 2.34 (Ardeberg, A. 1973, *Astron. Astrophys.*, in print).
- III. A Method for Absolute Calibration of Objective-Prism Plates Suitable for Computer Reduction (Ardeberg, A., Virdefors, B. 1972, *Astron. Astrophys.* 20, 177).
- IV. Spectrographic and photometric observations of Supergiants and Foreground stars in the direction of the Large Magellanic Cloud (Ardeberg, A., Brunet, J.-P., Maurice, E., Prévot, L. 1972, *Astron. Astrophys. Suppl.* 6, 249).
- V. On the Extended van Wijk Sequence in the Large Magellanic Cloud (Ardeberg, A. 1972, *Astron. Astrophys.* 19, 384).
- VI. A Photometric Study of Nova Doradus 1971a in the Large Magellanic Cloud (Ardeberg, A., de Groot, M. 1973, *Astron. Astrophys.* 26, 53).
- VII. The 1972 Supernova in NGC 5253. Photometric results from the first observing season (Ardeberg, A., de Groot, M. 1973, *Astron. Astrophys.*, in print).
- VIII. Photometry and Spectroscopy of the 1972 Supernova in NGC 5253 (Ardeberg, A., de Groot, M. 1973, *Proceedings of the International Conference on Supernovae, Lecce, Italy, May 7—11, 1973*).

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Physical parameters of stars with hot and extended atmospheres

Abstract: Continuum energy distribution of O5—G0 stars can be closely represented by spectral gradients. The gradient versus spectral-type relation depends on luminosity class and has a small spread. From objective-prism plates absolute gradients can be obtained. Luminous stars in the Large Magellanic Cloud and galactic foreground stars were studied. Results of spectrography and UBV photometry are presented. A recalibration was made of the extended van Wijk sequence in the Large Magellanic Cloud. Nova Dor 1971a was followed by UBV photometry from $V=11.8$ to $V=21.5$. It was of a fairly fast type and very blue. The 1972 supernova in NGC 5253 was observed by UBV photometry and spectrography. It was the first time light and colour curves were established for a type I supernova over a large time interval. A second-order light and colour fluctuation was found.

Key words: Energy distribution — spectral gradients — high-luminosity stars — novae — supernovae.

Introduction

Stars with hot and extended atmospheres are of particular significance from several points of view. Their spectra are normally relatively free from crowding lines and thus offer special facilities for the study of spectral energy distribution. They have luminosities in the visual and photographic spectral regions high enough to make them detectable also at larger distances, and include objects with exceedingly high energy production. Their ages are often low, making them outstanding tracers of stellar birth loci and thus of large-scale galactic structure. Their comparatively rapid evolution gives them an important role in the study of stellar evolution and in investigations including studies of evolutionary parameters for stellar aggregates.

Whilst relevant data on spectral energy distribution are essential for the

study of stellar atmospheres, such data are also necessary from many aspects of observational astronomy. Intrinsically, stars with hot and extended atmospheres are excellent distance indicators. In order to take full advantage of this property it is, however, essential to have good knowledge of their spectral energy distribution. Such knowledge is necessary for a relevant classification of the stars and also in order to distinguish the true stellar energy parameters from those influenced by interstellar absorption.

Spectral energy distribution

The fundamental importance of an enlarged knowledge concerning the spectral energy distribution of stars has often been emphasized (Unsöld, 1955, Chalonge, 1958, Code, 1960, Oke, 1965). Early attempts at photographic determinations of spectral energy parameters were made in Greenwich (Greaves et al., 1934) and in Göttingen (Kienle et al., 1938). However, real progress in the field was made first when the use of photoelectric devices such as narrow-band photometers and scanners gave possibilities for wide-range measurements in systems easily reproducible.

The continuum energy distribution for O5—G0 stars was studied by the writer (Ardeberg, 1969) in terms of spectral gradients. All luminosity classes were covered. Available observational material permitted a wide wave-number interval, $\lambda^{-1} = 0.93$ to $\lambda^{-1} = 3.13$, to be included. Special regard was given to the choice of observational data, to the wave-number bases of the gradients, and to the influence of interstellar absorption. The material was reduced to a common absolute system.

The results obtained show firstly, that the continuum energy distribution of O5—G0 stars can be very closely represented by spectral gradients, provided that a proper choice of wave-number bases is made. Secondly, it is evident that the various observational series adopted can be reduced to a single system without introduction of systematic differences. Thirdly, it is demonstrated that the influence of interstellar absorption is very strong. The reduction for this effect is shown to be free from systematic errors also for very high amounts of interstellar reddening. Further, the spread in the gradient versus spectral-type relations is proved to be almost entirely due to statistical errors in the calculated apparent gradients, i.e. due to observational errors. Significant differences between the luminosity classes are moreover demonstrated for the gradient versus spectral-type relations. These differences are present throughout the wave-number interval studied.

Recently, Chalonge and Divan (1973) published new observational data for parameters in the Barbier—Chalonge—Divan system. In their article they give a calibration of the gradient Φ_b , identical to the gradient $\Phi_{2.34}$ as given by the writer, the wave-number interval covered being $\lambda^{-1} = 2.20$ to $\lambda^{-1} = 2.48$. The calibration is made for low-luminosity stars only. The agreement between their results and those of the writer is almost perfect for stars of spectral type B3 and later (Ardeberg, 1973 a). For stars of earlier spectral type the gradients given by Chalonge and Divan are higher than those given by the writer. However, using the data given by Chalonge and Divan and reducing for the influence of the interstellar absorption in the manner discussed earlier (Ardeberg, 1969), the agreement becomes perfect also for the stars of very early spectral type.

Chalonge and Divan (1973) state the differences between the gradient versus spectral-type relations of different luminosity classes to be negligible. Using their data and reducing for the effect of interstellar absorption it was shown by the writer that the new data given by Chalonge and Divan in fact fully support his conclusions from 1969 (Ardeberg, 1973 a) concerning the dependence of the gradient values on luminosity class.

The knowledge of the continuum energy distribution for a number of objects in a stellar field may be used to obtain very good intensity measures for other stars in the same field by means of objective-prism plates of low dispersion (Ardeberg and Virdefors, 1972). Advantage can be taken of stars within the field for which integral magnitudes and spectral and luminosity classifications are available. In this way both monochromatic magnitudes and absolute gradients can be determined for great numbers of faint stars. The method also means that any light loss or image crowding due to calibration devices is avoided. The errors in the obtained spectral energy parameters are shown to be small, also for objective-prism plates with un-widened images. The calibration method is applicable to any objective-prism plate and any system of spectrophotometric measurements.

High-luminosity stars in the Large Magellanic Cloud

For many reasons stars with hot and extended atmospheres are difficult to locate in large numbers in our own galaxy. As they are to be found mainly in the galactic plane, studies are moreover hampered by star crowding, presence of interstellar matter, bright nebulae etc. External galaxies seen more or less pole-on should in principle provide better observational pos-

sibilities. In this case, however, apparent luminosities are too faint for detailed studies even in the case of M 31.

A unique possibility for detailed work on high-luminosity stars is offered by the Magellanic Clouds. The advantages of these systems are several. The distance can be regarded as accurately determined and differences in distance moduli for the various member stars are negligible within any one of the two Clouds. Interstellar absorption is known to be small in the Magellanic Clouds. The galactic latitude is favourably high and galactic foreground absorption is low.

The Large Magellanic Cloud is the most advantageous of the two Magellanic Clouds, being much richer in stars and having a somewhat smaller distance modulus than the Small Magellanic Cloud.

A survey of high-luminosity stars in the Magellanic Clouds was made by Feast et al. (1960). They gave 105 objects as members of the Large Magellanic Cloud. The HDE Catalogue was used as the basic finding list for probable Cloud members. Consequently, primarily the brightest stars of early spectral type were included.

Sanduleak's (1970) objective-prism survey of the Large Magellanic Cloud includes stars fainter than the HDE. However, being an objective-prism spectral-classification work, it must necessarily be biased with respect to spectral type.

Fehrenbach and Dufлот (1970, 1973) made a different approach, using radial velocities measured on plates taken with a radial-velocity astrograph. With these radial velocities as membership criteria no spectral-type bias was introduced.

With the Catalogues of Fehrenbach and Dufлот as a finding list an investigation was made of the high-luminosity stars of the Large Magellanic Cloud and of a number of galactic foreground stars (Ardeberg et al., 1972). This work was based on spectral classifications and radial velocity measurements in slit spectrogrammes of intermediate dispersion and on photoelectric UVB photometry. The limiting magnitude is $V = 14.0$.

Using the spectral classes, radial velocities and photometric data as criteria membership was discussed. 409 stars are presented as members of the Large Magellanic Cloud, while 42 stars are possible members, and 132 stars are found to be galactic foreground objects. 19 of these foreground stars have high radial velocities.

The results obtained mean a considerable increase in our observational data, primarily concerning members of the Large Magellanic Cloud, but also for stars belonging to the galactic foreground. The study and discussion of the characteristics of individual spectra, velocity shifts of stellar lines

and photometric data give contributions to our knowledge of the physical parameters of high-luminosity stars in the Large Magellanic Cloud. Further, it increases our knowledge concerning bright nebulae and absorbing matter and its interaction with the stars within the Large Magellanic Cloud.

For the photometric observations in the Large Magellanic Cloud the extended van Wijk sequence (van Wijk, 1952, Bok and Bok, 1960) was chosen as local, secondary standard. It was found that the ultraviolet magnitudes of the stars in this sequence were not compatible with those of the primary standard stars in the E regions (Cousins and Stoy, 1962, Cousins, 1967). Thus a special series of observations was made to provide a reliable connection to the E region standard stars for both zero points and colour equations (Ardeberg, 1972). These observations should make the stars concerned good local standards for photometric work in the field of the Large Magellanic Cloud.

Novae and supernovae

Novae and supernovae do not only constitute two of the most spectacular types of objects in astronomy. They also hold key positions in the stellar evolutionary cycle and constitute exceedingly long-range distance indicators. Novae and supernovae show, apart from the level of their maximum luminosity, seemingly equal aspects, yet the physical processes behind the two types of events are entirely different (Schatzman, 1965). Both have in common an urgent need of compatible observational data, especially for the intervals around and before luminosity maximum and for late evolutionary phases (Ardeberg, 1973 b). Normally, the only practical way to obtain long-range compatible observations is to make wide-band photometry with unchanged equipment as frequently as possible, either until the object has reached a stable luminosity level or down to the limiting magnitude of the instrumentation.

When attempting to derive the intrinsic properties of novae we are restricted by much the same difficulties as in work with high-luminosity stars in general. Great efforts have been made to secure adequate observational data for novae in M 31 (Arp, 1956). However, because of the restricted magnitude interval observable for these novae only limited conclusions can be drawn from this material.

As for high-luminosity stars in general, the Magellanic Clouds provide exceptional observational facilities for studies of novae. The relatively

accurate distance and very low interstellar absorption are matched by an expected apparent magnitude range of novae that is still within feasible limits for larger telescopes.

The first nova in the Magellanic Clouds to be covered by fully compatible photometry over a major part of its evolution was Nova Doradus 1971a in the Large Magellanic Cloud (Ardeberg and de Groot, 1973 a). Starting at the principal luminosity maximum, the UBV observations were continued over a period of 430 days and down to the limiting magnitude of the instrumentation employed. This corresponds to a magnitude interval $V = 11.8$ to $V = 21.5$ or an absolute visual magnitude interval of -6.9 to $+3.0$.

The light and colour curves were derived and discussed for Nova Doradus 1971a. The nova was found to be of a fairly fast type with three pronounced luminosity maxima. About 20 days after the principal luminosity maximum it displayed a marked change of decline rate, followed by a conspicuous luminosity plateau with a duration of about 6 days. The nova was very blue throughout its evolution in (B-V) as well as in (U-B).

Different measures of radiation outburst energy were discussed and the true bolometric radiation outburst energy was estimated to about 4×10^{45} ergs, whereas the radiation outburst energy normally referred to, the "V outburst energy" was 3×10^{44} ergs. The ejection of material was discussed.

Using Nova Doradus 1971a as an independent distance indicator for the Large Magellanic Cloud we obtain a distance modulus of 18.75 , which is exactly equal to the currently accepted one (Westerlund, 1973).

Because of the low frequency of supernova events, collection of observational data for supernovae is a difficult task. Most supernovae detected occur in galaxies too distant to allow anything more than fragmentary photometric data to be obtained. It is therefore of importance that any apparently bright supernova is covered by all sorts of observations feasible. This need of observations should be especially stressed for supernovae of type I, presenting at the same time exceedingly high luminosities, low frequencies and bewildering physical properties. The actual observational material for type I supernovae is very scarce.

The 1972 supernova in NGC 5253 was the first type I supernova observed in U, B and V with the same equipment over a longer period (Ardeberg and de Groot, 1973 b, 1973 c). The extended observations provided "normal" light and colour curves, while the first observing night was devoted to a combination of regular UBV photometry and high-speed monitoring.

For the B light curve there is good resemblance with the photographic light curve of the 1937 supernova in IC 4182 (Minkowski, 1964). The light-

curve parameters of the 1972 supernova in NGC 5253 are in general similar to the results of compilations presented by Zwicky (1965) and Pskovskii (1970). The absolute magnitude at luminosity maximum is found to be $B = -20.25$.

A comparison between the (B-V) colour curve for the 1972 supernova in NGC 5253 and results of compilations by Mihalas (1963) and Pskovskii (1970) reveal great similarities, although these compilations cover time intervals considerably smaller than that studied for the 1972 supernova in NGC 5253. On the other hand the (U-B) curve of the same supernova is very different from that compiled by Pskovskii (1970). The (U-B) curve of the 1972 supernova in NGC 5253 displays two plateau parts. The first plateau is situated between 30 and 60 days after the B luminosity maximum and has $(U-B)_0 = +0.1$. The second plateau starts about 160 days after the B luminosity maximum. It has $(U-B)_0 = +0.9$ and seems to be very stable at this level for at least 100 days (Ardeberg and de Groot, 1973 c) and fairly stable at least another 100 days (Ardeberg and de Groot, 1973 d). The (U-B) curve derived by Pskovskii (1970) shows a smoothly rising branch up to about 70 days after luminosity maximum and to $(U-B)_0 = +0.5$. The curve then equally smoothly returns to $(U-B)_0 = 0.0$ about 130 days after luminosity maximum. However, the last part of this curve is based on very few data points. The appearance of the spectra (Ardeberg and de Groot, 1973 c) and their evolution with time fully support the (U-B) curve as given by Ardeberg and de Groot (1973 b, 1973 c, 1973 d).

The result of the high-speed monitoring during the first night of observations is that whereas no fluctuations with a time scale less than one hour were found, the presence of a secondary decay fluctuation is demonstrated, having a period between 0.1 and 1.0 days and found for all light and colour curves. It is evident that at an early stage any core activity should be effectively masked by the high optical depth of the outer layers. The second-order fluctuation present suggests the existence of a variable ejection rate.

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